The 1993 Mississippi River Flood: A One Hundred or a One Thousand Year Event?

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ABSTRACT

Power-law (fractal) extreme-value statistics are applicable to many natural phenomena under a wide variety of circumstances. Data from a hydrologic station in Keokuk, Iowa, shows the great flood of the Mississippi River in 1993 has a recurrence interval on the order of 100 years using power-law statistics applied to partial-duration flood series and on the order of 1,000 years using a log-Pearson type 3 (LP3) distribution applied to annual series. The LP3 analysis is the federally adopted probability distribution for flood-frequency estimation of extreme events. We suggest that power-law statistics are preferable to LP3 analysis. As a further test of the power-law approach we consider paleoflood data from the Colorado River. We compare power-law and LP3 extrapolations of historical data with these paleo-floods. The results are remarkably similar to those obtained for the Mississippi River. Recurrence intervals from power-law statistics applied to Lees Ferry discharge data are generally consistent with inferred 100- and 1,000-year paleofloods, whereas LP3 analysis gives recurrence intervals that are orders of magnitude longer. For both the Keokuk and Lees Ferry gauges, the use of an annual series introduces an artificial curvature in log-log space that leads to an underestimate of severe floods. Power-law statistics are predicting much shorter recurrence intervals than the federally adopted LP3 statistics. We suggest that if power-law behavior is applicable, then the likelihood of severe floods is much higher. More conservative dam designs and land-use restrictions may be required.

INTRODUCTION

The great flood of 1993 in the upper Mississippi River basin once again focused attention on the reliability of flood-frequency forecasts. A fundamental question in calculating flood probabilities is whether the statistical methods used provide an adequate estimate for expected recurrence intervals. The results presented in this paper suggest that federally adopted techniques for flood-frequency forecasting in the Mississippi River basin seriously underestimate recurrence intervals of extreme floods.

Floods are complex phenomena involving coupled meteorological and hydrological processes; they are also influenced by human facilities and activities, including dams, channelization, and land use. Recurrence intervals are a means of expressing the odds of a given magnitude flood being exceeded in any year and are an important factor in flood control, land-use regulation, emergency planning, and insurance considerations.

Historically, flood-frequency estimation has been treated strictly on an empirical basis and a wide variety of statistical distributions have been used. The most commonly used frequency-magnitude distributions in hydrology can be divided into four groups: the normal family (normal, log-normal, log-normal type 3), the general extreme-value (GEV) family (GEV, Gumbel, log-Gumbel, Weibull), the Pearson type 3 family (Pearson type 3, log-Pearson type 3), and the generalized Pareto distribution. Stedinger and others (1993) provide an excellent discussion and review of these different distributions. Severe floods are associated with the tails of the flood-frequency distributions. Two extreme behaviors for the tails are power-law and exponential. Power-law tails give much shorter estimates of flood recurrence intervals than exponential tails.

The standard approach for flood-frequency estimation is to consider a sequence of maximum annual floods and obtain the best empirical fit of the chosen statistical distribution to this data set. The best fit is obtained by equating the statistical moments of the data to the distribution. Additional constraints, such as the censoring of outlier points, are commonly used. In the United States, the federally adopted approach to flood-frequency estimation is to fit logarithms of the annual peak discharges to the Pearson type 3 distribution (U.S. Water Resources Council, 1982); some countries have adopted other types of distributions. Australia uses log-Pearson type 3 (LP3) distributions as their standard for flood-frequency estimation. However, Vogel and others (1993) have argued that in many parts of Australia generalized Pareto distributions perform significantly better than LP3.

In this paper the validity of power-law statistics in estimating floods is considered. Many natural phenomena satisfy power-law (fractal) frequency-magnitude statistics. Examples are found in a wide variety of circumstances and include fragmentation, earthquakes, volcanic eruptions, mineral deposits, and land forms (Turcotte, 1992). Turcotte and Greene (1993) have argued the validity of power-law statistics to floods in the United States utilizing 14 USGS bench-mark gauging stations. Turcotte (1994) extended these arguments by studying 1,200 gauging station records across the United States.

We examine the great Mississippi River flood of 1993 with power-law and LP3 analyses, concentrating on historical flood records from Keokuk, Iowa (Figure 1). This station has a long record (1879–present) and is representative of flood discharges on the Mississippi River during the great flood of 1993. A difficulty with calculating recurrence intervals is that they are usually based on hydrologic station records of continuous discharges, which are generally short, on the order of a hundred years or less. As a further test of the power-law approach we consider paleofloods on the Colorado River in the Grand Canyon of Arizona. Paleoflood data give an estimate of discharge for single extreme events over a much longer time period.

DISTRIBUTIONS

Power-Law

The volumetric discharge q(t) at a point on a river is generally a continuous time series. We are concerned with the extreme values of this time series and define Q(T) to be the maximum discharge associated with a recurrence interval of T years. For example, Q(100) would be the maximum discharge (flood) that has an average recurrence interval of 100 years, i.e., in any one year, there is a one-in-one hundred chance of the peak discharge equaling or exceeding Q(100).

The power-law distribution for flood-frequency takes the form:

$$Q(T) = CT^{\alpha} \qquad \text{Eq. 1}$$

where C and α are regression coefficients. Taking the logarithms of both sides of Equation 1 gives:

$$\log Q(T) = \alpha \log T + C' \qquad \text{Eq. 2}$$

This scale invariant distribution can be expressed in terms of F, the ratio of the peak discharge over a 10-year interval to the peak discharge over a 1-year interval. With self-similarity, the parameter F is also the ratio of the 100-year peak discharge to the 10-year peak discharge:

$$F = \frac{Q(10)}{Q(1)} = \frac{Q(100)}{Q(10)} = \text{constant} \qquad \text{Eq. 3}$$

In terms of α we have:

$$F = 10^{\alpha} \qquad \text{Eq. 4}$$

If the flood-frequency factor F is large the ratio of the 10-year to the 1-year flood will be large, if F is small the ratio will be small. The parameter α is the slope of a log(Q) versus log(T) plot. Parameters α and F are related by Equation 4. As in all applications of power-law distributions to natural processes, there are upper and lower limits to the validity of the power-law.

Log-Pearson Type 3

The LP3 distribution has been adopted by Federal agencies in the United States for flood-frequency estimation (U. S. Water Resources Council, 1982). The LP3 distribution describes a random variable whose logarithm is a Pearson type 3 distribution. The logarithms of an annual flood series are used to calculate the mean, standard deviation, and skew. These three moments determine the shape, scale, and location parameters that characterize the LP3 distribution. The LP3 fit involves three empirical constants whereas the power-law fit involves only two. The U. S. Water Resources Council (1982) outlines the application of the LP3 to an annual flood series. In our analyses, we use these methods for dealing with outliers, conditional probability, weighted skew, and K coefficients. The weighted skew coefficient is calculated using the generalized skew coefficient as obtained from the U. S. Water Resources Council (1982) generalized skew map.

DATA ANALYSIS

Annual and Partial-Duration Flood Series

An annual flood is the peak discharge during a water year, where the water year is defined to be a 12-month period from October 1 of the previous year through

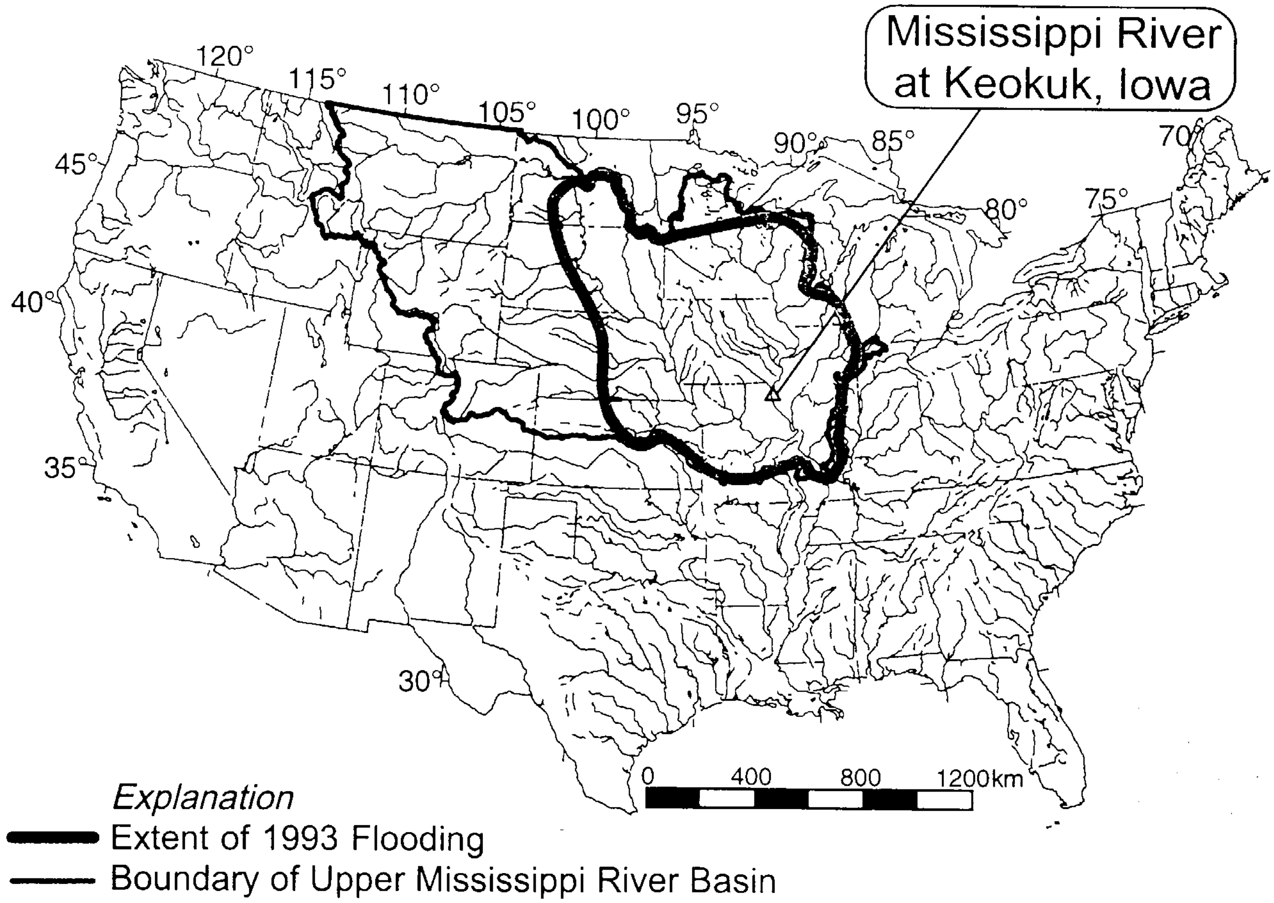

Figure 1. Map of the United States showing the upper Mississippi River basin and the extent of flooding during 1993 (U.S. Geological Survey, 1996). Also shown is the location of the Keokuk, Iowa, stream-flow-gauging station used in this paper.

September 30 of the water year. For example, the 1995 water year extends from October 1, 1994, through September 30, 1995. Data sets used in our analyses consist of mean daily discharges and are used to determine the peak discharge (flood) in each water year. The annual flood series is the sequence of annual floods over a specified interval of time.

A major problem with an annual flood series is that several floods in a given water year may be larger than the annual flood in another water year. To overcome this difficulty, we also consider a partial-duration flood series where more than one flood can occur in a water year. In our definition of a partial-duration flood series, peak discharges must be separated by at least thirty days in order to be classified as separate floods. For a given water year we take Q, the maximum mean daily discharge (flood) for that year, and delete all values thirty days on either side. We then take the next largest Q, and again delete all values thirty days on either side. We continue until we have the six largest Q's for that water year. This process is repeated for the other water years. The total number of water years in our data set is N. To arrive at the partial-duration flood series the 6N values of Q are ordered from largest to smallest. Our final partial-duration flood series is the N largest ordered Q's, i.e., the subset of largest ordered Q's that corresponds with the number of water years considered.

Other definitions for a partial-duration flood series can be made (Hipel, 1994). For example, we could have required that the Q's in the partial-duration series be separated by sixty days instead of thirty days, or applied the criteria that the flow q must drop to some fraction, say 50 percent, of the flood value Q before another flood was chosen. Another approach is to use the peaks over threshold method (Hosking and Wallis, 1987; Davison and Smith, 1990; and Barrett, 1992). In this method the peaks over a chosen threshold, typically one to five per year, define the partial-duration flood series. We have applied several partial-duration definitions to our data sets and find that the differences are small; as such we only use the definition that Q's are separated by at least thirty days.

For both the annual flood series and the partial-duration flood series the Q's of each flood are ranked ($r = 1, 2, 3, \ldots, N$) from largest to smallest, where N is the number of water years in the data set. If Q is equaled or exceeded r times in N years (N is large), then the recurrence interval in years is T = N/r. As an example, if we take a data set with N = 114 water years, the largest Q is assigned a recurrence interval of T = 114/1 = 114 years, the second largest T = 114/2 = 57 years, and so forth until the 114th value with T = 114/114 = 1 year. This is entirely equivalent to a cumulative frequency/size analysis where r, the cumulative number greater than a size, is plotted as a function of size. This technique is routinely applied to the frequency/size statistics of earthquakes and other extreme-value events (Turcotte, 1992).

Data

On the basis of length of record and drainage basin size we have chosen gauging station 05474500 on the Mississippi River at Keokuk, Iowa, to be representative of flooding statistics on the Mississippi River during the great 1993 flood. The drainage area upstream of this station is 308,000 km^2 and a 117-year record of mean daily discharges from 1879 to 1995 is available (Slack and Landwehr, 1992; May, 1996). We use this data to construct both annual and partial-duration flood series for the gauge at Keokuk, Iowa. In our analyses, we calculate flood-frequency forecasts that would be made with data available before the great 1993 Mississippi River flood occurred (water years 1879–1992) and then compare how the forecasts change with the addition of the 1993 flood (water years 1879–1995). For each time period, we estimate flood-frequency using LP3 applied to annual series, and compare these with power-laws applied to partial-duration series.

One of the most extensive studies of paleofloods was carried out by O'Connor and others (1994). These authors used the stratigraphic record to quantify large floods during the last 4,500 years at Axehandle Alcove on the Colorado River in the Grand Canyon, Arizona. We compare their geologic estimates of the lower bounds of discharges associated with the largest paleofloods that occurred in the last 4,500 years with historical discharge data available from water years 1921–1962 at Lees Ferry, Arizona (ADAPS, 1996). The Lees Ferry gauge at USGS station 09380000 has a drainage area of 289,600 km^2 and is located on the Colorado River in Arizona, 3 km upstream of Axehandle Alcove. Unregulated daily discharge data exists for water years 1921–1962. Discharge has been regulated by the Glen Canyon Dam since the beginning of the 1963 water year.

RESULTS

Mississippi River at Keokuk, Iowa

In Figure 2 (1879–1992) and Figure 3 (1879–1995) the logarithms of the Keokuk floods, log(Q), are

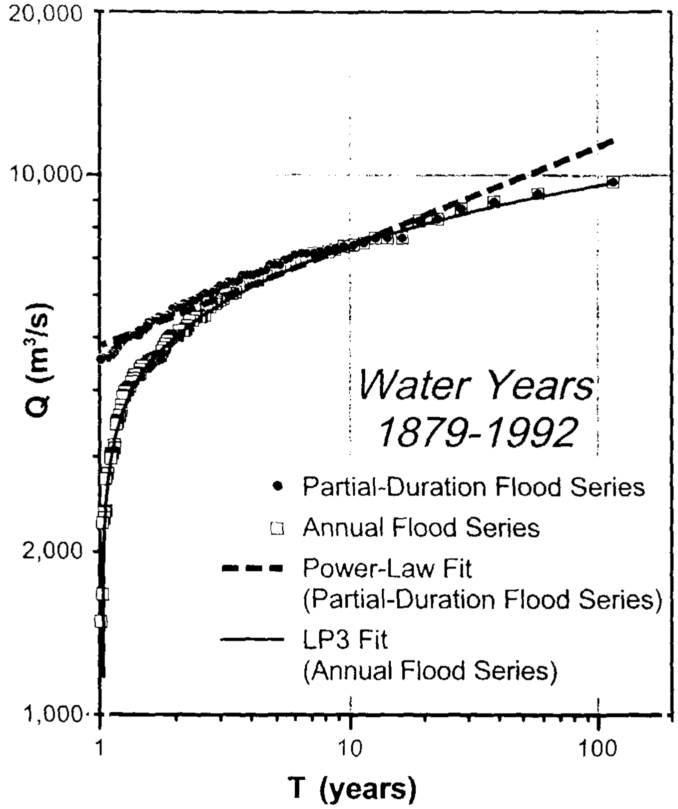

Figure 2. Dependence of the maximum daily discharge Q associated with the period T on the period T. The partial-duration and annual flood series for station 05474500 on the Mississippi River at Keokuk, Iowa, are shown for water years 1879–1992. Also included is the least-squares power-law fit for the partial-duration flood series, as well as the log-Pearson type 3 (LP3) distribution based on the annual flood series and the procedures of Bulletin 17B (U. S. Water Resources Council, 1982).

plotted against the logarithms of the recurrence intervals, log(T). For both time periods, the annual and partial-duration flood series strongly diverge for periods of less than about 5 years because multiple floods in some water years are much larger than the largest flood in other water years.

For a power-law distribution of floods the relation between log(Q) and log(T) is given in Equation 2. In log-log space a power-law distribution corresponds to a straight line with slope α and intercept C'. The best-fit straight lines to the partial-duration Keokuk flood series for 1879–1992 and 1879–1995 using a least-squares fit in log-log space give respectively $\alpha = 0.19$, 0.20 and C' = 3.69, 3.68 with an $r^2 = 0.97$, 0.94. The corresponding flood-frequency factors from Equation 4 are F = 1.53 and 1.58. The best-fit straight lines for the two time periods are given separately in Figures 2 (1879–1992) and 3 (1879–1995) and together in Figure 4. Extrapolation of the straight line for water years 1879–1992 to the maximum daily flow during the 1993 flood, Q = 12,300 m^3/s, results in a recurrence interval of T = 151 years.

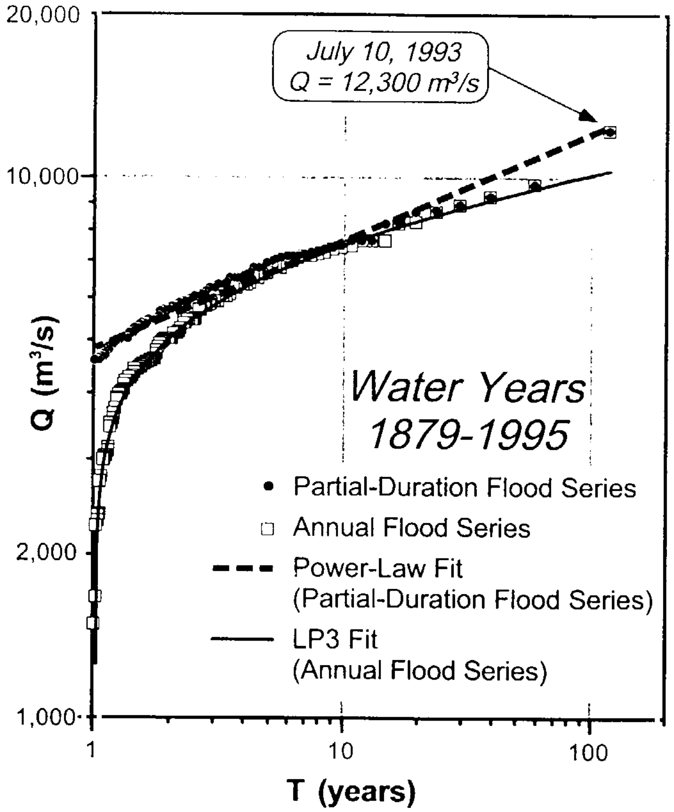

Figure 3. Same as Figure 2 except the period considered is water years 1879–1995. The maximum daily discharge associated with the 1993 flood is shown.

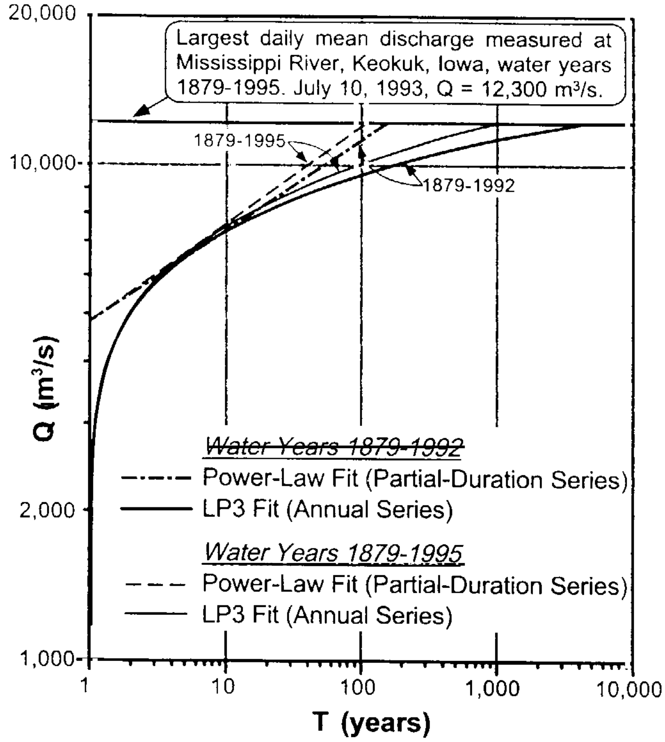

Figure 4. The power-law and LP3 curves given in Figures 2 and 3 are extrapolated to the maximum flow during the 1993 flood (Q = 12,300 m^3/s). For the 1879–1992 flood series the recurrence interval for the 1993 flood is 151 years based on power-law statistics and 4,300 years based on LP3 analysis. For the 1879–1995 flood series the recurrence interval is 115 years based on power-law statistics and 1,000 years based on LP3 analysis.

With the addition of 1993–1995 (water years 1879–1995) this extrapolation is reduced to a recurrence interval of T = 106 years. The two forecasts do not differ significantly from one another (Figure 4) and are consistent with the 1993 flood being a typical 100-year flood.

Another consideration is whether the extrapolated recurrence intervals for Keokuk would be significantly different for much smaller subsets of the 1879–1995 period. Using the same procedure for two 32-year periods, extrapolation of the best fit power-law line to a discharge the size of the great flood of 1993 results in recurrence intervals at Keokuk of 179 and 165 years for the periods 1900–1931 and 1932–1963. The results for the two 32-year periods do not vary significantly from the recurrence intervals of 151 and 106 years as obtained for the 114-year (1879–1992) and 117-year (1879–1995) periods.

The best LP3 distribution is found using the annual flood series from the gauge at Keokuk, Iowa, and the procedures as outlined by the U.S. Water Resources Council (1982). The result using water years 1879–1992 is given in Figure 2. After two low outliers were censored, the logarithms of the remaining 112 points were used to obtain the first three moments: $\overline{X}$ = mean = 3.70, S = standard deviation = 0.14, and G = station skew = –0.36. The weighted skew coefficient, $G_W = -0.37$, is calculated using a generalized skew coefficient of $\overline{G} = -0.4$. The best-fit LP3 distribution given in Figure 2 has considerable curvature resulting in long recurrence intervals for severe floods. The extrapolation of this LP3 curve to the great flood of 1993, Q = 12,300 m^3/s, is shown in Figure 4. For the time period 1879–1992, the resulting recurrence interval is T = 4,300 years, almost thirty times longer than what we obtained using power-law statistics for the same time period.

We have also used the LP3 distribution to obtain a best-fit LP3 curve for the annual flood series at Keokuk from 1879–1995. Again, two low outliers were censored, and we found $\overline{X} = 3.70$, S = 0.14, G = –0.22, and $G_W = -0.25$. The resulting LP3 curve is given in Figure 3 and again has considerable curvature. Extrapolation of the LP3 curve to the great flood of 1993 (Q = 12,300 m^3/s) is also shown in Figure 4. For the time period 1879–1995, the extrapolated recurrence interval is T = 1,000 years, about ten times longer than what we found using power-law statistics for the same time period.

The inclusion of the 1993 Mississippi River flood in the LP3 analysis results in the two recurrence interval estimates being very different, T = 4,300 years (1979–1992) versus T = 1,000 years (1879–1995). The recurence

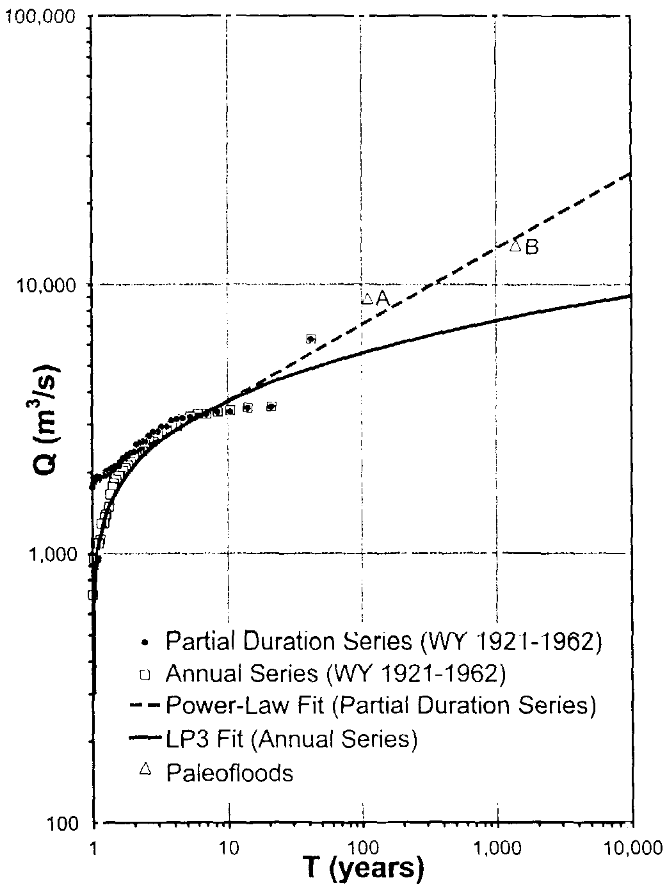

Figure 5. Dependence of the maximum daily discharge Q associated with the period T on the period T for the Colorado River in the Grand Canyon, Arizona. The partial-duration and annual flood series for station 09380000 on the Colorado River at Lees Ferry, Arizona, are shown for water years 1921–1962. The least-squares power-law fit to the partial-duration flood series and LP3 distribution based on the annual flood series are also included. Points A and B are estimates of two paleofloods based on the stratigraphic record at Axehandle Alcove obtained by O'Connor and others (1994).

intervals found using LP3 are considerably more sensitive to a single large flood (in this case the great 1993 Mississippi River flood) than those found using power-laws.

Colorado River Paleofloods

Using data from the Lees Ferry gauge on the Colorado River for water years 1921–1962, we construct the partial-duration and annual flood series, ordering them from largest to smallest (r = 1, 2, 3, ..., 42). For a power-law distribution, the best-fit straight line to the partial-duration flood series using a least-squares fit in log-log space gives a = 0.28, C' = 3.28, r^2 = 0.92 and F = 1.93. This straight-line fit is given in Figure 5. Using the best-fit LP3 distribution to the annual flood series with no outliers censored, the first three moments are $\overline{X}$ = 3.32, S = 0.20, and G = –0.34. The weighted skew coefficient of G_W = –0.23 is calculated using a generalized skew coefficient of $\overline{G}$ = 0.00. The LP3 fit has much more curvature in log-log space when compared to the power-law fit (Figure 5) resulting in longer recurrence intervals for severe floods.

Two paleoflood discharge estimates from stratigraphic interpretations of O'Connor and others (1994) at Axehandle Alcove are plotted as points A and B in Figure 5. Point A correlates with sediments deposited after 520–280 calendar years BP and a peak flow greater than Q = 8,800 m^3/s. Point A is interpreted to be the historic Colorado River flood of 1884. The flow from stratigraphic interpretation (Q = 8,800 m^3/s) compares favorably with rough historical estimates (Q = 8,500 m^3/s). We assign this point a recurrence interval of 112 years. Extrapolation to the Colorado River flood of 1884 (Q = 8,800 m^3/s) using the Lees Ferry power-law fit suggests a recurrence interval of T = 200 years. Extrapolation of the LP3 curve suggests a much longer recurrence interval of T = 7,000 years. Point B is a single great flood with a flow greater than Q = 14,000 m^3/s and was dated by O'Connor and others (1994) at 1,600–1,200 calendar years BP. We assign this point a recurrence interval of T = 1,400 years. This great 1,000-year paleoflood is remarkably close to the power-law extrapolation and greatly exceeds any flood forecast by LP3 analysis.

DISCUSSION

The federally adopted approach for flood-frequency estimation uses LP3 distributions fit to annual flood series. Our primary objection to this approach is that the use of the annual flood series introduces an artificial curvature in log-log space that leads to an underestimate of severe floods. There are often two, three, or even more partial-duration floods in one year that exceed annual floods in other years. In an annual flood series, multiple floods during a water year are ignored since only one flood per water year is considered. In Figures 2, 3, and 5, the partial-duration flood series is well represented by power-law statistics whereas the annual flood series is not.

For power-law analyses, the great 1993 Mississippi River flood was a 100-year flood, whereas for the LP3 analysis it was a 1,000- to 10,000-year flood. In many ways the 1884 Colorado River flood is analogous to the 1993 Mississippi River flood. These two floods are either typical 100-year floods or 1,000-year (or more) floods that happened to occur during this 100-year time interval. In both cases, the partial-duration series is better represented by power-law statistics than LP3. The power-law statistics forecast much shorter recurrence intervals supporting the idea that these two floods are typical 100-year floods. Finally, the power-law fit to the historical discharges at Lees Ferry on the Colorado River extrapolates extremely well to both of these stratigraphically interpreted paleofloods at Axehandle

Alcove (Figure 5). The paleoflood dated at 1,600–1,200 years BP has a discharge 60 percent greater than the 1884 flood and is a good candidate for the "true" 1,000- to 10,000-year Colorado River flood.

Up to this point use of power-law versus LP3 analyses for flood-forecasting has been strictly empirical. We now address the question, is there a scientific rationale for the applicability of power-law statistics to severe floods? Many natural phenomena satisfy power-law (fractal) frequency-magnitude statistics and evidence is accumulating to support an underlying physical basis (Feder, 1988). This evidence includes systems, such as the logistic map (May, 1976), that exhibit deterministic chaos and often satisfy power-law statistics. Further evidence comes from a variety of both deterministic and statistical models, such as the sand-pile model (Bak et al., 1988), that exhibit self-organized criticality and also yield power-law frequency-size distributions.

A river flow is a classic example of a time series. A time series is self-similar if its spectral power density has a power-law dependence on frequency. Self-similar time series are often referred to as fractional Gaussian noises or fractional Brownian walks (Mandelbrot and Wallis, 1969). The work of Hurst and others (1965) supports the application of power-law distributions to flood-frequency estimation. Hurst studied the flow of the Nile River and introduced rescaled range analysis. By performing a running sum of the river discharge to find the variations in reservoir storage, Hurst found that the reservoir storage is generally a fractional Brownian motion with a power-law dependence of the storage range on the interval of time considered.

An essential question with floods is whether the frequency-magnitude distribution obeys power-law, log-normal, or other statistics. If severe floods result from the successive addition of a sequence of random events, such as rainstorms, then in analogy to the range of reservoir storage, the floods may obey power-law statistics. The 1993 flood on the Mississippi River was caused by a sequence of severe rainstorms over a period of months, accumulating to give a very high flood run-off. Although the processes that lead to a flood are very complex, it appears reasonable to hypothesize that severe floods behave as fractional Brownian walks rather than fractional Gaussian noises and as a result may satisfy power-law statistics.

CONCLUSIONS

We have applied power-law statistics to the partial-duration flood series at Keokuk, Iowa, for the periods 1879–1992 and 1879–1995, and find that the great Mississippi River flood of 1993 ($Q = 12,300$ m^3/s) would have a recurrence interval of $T = 151$ and 115 years. We have also applied the log-Pearson type 3 distribution to the annual flood series at this station and find that the 1993 Mississippi flood would have a recurrence interval of $T = 4,300$ and 1,000 years. According to power-law statistics this flood was a rather typical 100-year flood, whereas for LP3 it was a 1,000- to 10,000-year flood. In addition, the LP3 analysis is considerably more sensitive to the inclusion of the single large flood (the great 1993 Mississippi River Flood) than the power-law analysis.

As a further test of the two methods of flood-frequency forecasting we have considered a record of paleofloods on the Colorado River. The results are remarkably similar to those for the Mississippi River. Power-law recurrence interval estimates based on historical discharge data from Lees Ferry are generally consistent with inferred 100- and 1,000-year paleofloods from Axehandle Alcove, just downstream of Lees Ferry. On the other hand, LP3 analysis gives recurrence intervals that are orders of magnitude longer.

Although there will certainly be both upper and lower cutoffs on the applicability of power-law distributions, we argue that for the Keokuk and Lees Ferry gauges there is an excellent fit of the power-law distribution to the partial-duration flood series. If power-law fits are correct, then severe floods are much more likely to occur than flood-frequency forecasts based on the federally adopted log-Pearson type 3 methodology. More conservative designs for dams and land-use restrictions may be appropriate. We suggest using the power-law fit when extrapolating to arrive at estimates for the severity of future floods.

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